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FROST DAMAGE OF CONCRETE SUBJECT TO CONFINEMENT

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Abstract

When internal frost damage is observed in real concrete structures, the usual pattern is cracks with a preferred orientation parallel to the exposed surface. When exposing concrete with poor frost resistance to a standardised freeze/thaw test in the laboratory, the orientations of the resulting cracks are more or less random. The present study is an experimental study, which aims at investigating the influence of confinement during freeze/thaw action on the developed crack pattern. Confinement is established by mounting hose clamps on cylindrical test specimens, using similar test specimens without hose clamps as reference. The results show that confinement can change the outcome of a freeze/thaw test as regards extent of internal cracking, crack orientations, and amount of surface scaling. Thus it seems likely that the difference in confinement (and therefore also in stress state) can explain the different crack patterns observed in the field and in the laboratory.

1. Introduction

The study presented in the following emanated from a discussion at a meeting in 2014 in the Danish Society for Microscopy of Building Materials (FMIB).

In Denmark, the reference method of CEN/TS 12390-9 [1] is the most widely used method for testing concrete frost resistance. According to this test method, the frost resistance is quantified by measurement of surface scaling during 56 standardised freeze/thaw cycles for concrete specimens exposed to 3% NaCl solution on the test surface. It is not part of the test method to inspect the inner frost damage in the form of cracking. However, if test specimens after testing are impregnated with fluorescent epoxy, it is possible to observe the crack patterns. For concrete that is not frost resistant, this normally leads to a diffuse crack pattern with no distinct crack orientation.

If concrete from the field (walls, pavements, etc.) suffers from inner frost damage due to natural freeze/thaw exposure, and this concrete in a similar way is treated with fluorescent epoxy, the usual pattern is cracks with a preferred orientation parallel to the exposed surface.

Therefore, the discussion at the FMIB meeting concerned to what extent the laboratory test represents what takes place in concrete that is being exposed to a natural climate with freezing temperatures. The opinions could more or less be summarised in the following two conflicting standpoints:

A. The difference in crack patterns indicates that it may be different mechanisms that trigger internal frost damage in the laboratory and in the field. If it is not the same mechanism that causes damage in the laboratory as in the field, it puts strong limitations on what can actually be deduced from laboratory results about the frost resistance of concrete in service.
B. Ice formation is an expansive reaction. For other expansive reactions in concrete it is known that the crack pattern depends on the initial stress situation of the concrete. Alkali-silica reaction (ASR) is an example of this [2]. For concrete elements that are free to move in all directions, ASR leads to randomly orientated cracks, also known as map cracking. If the concrete is restrained in one direction, e.g. a loadbearing bridge column or a pre-stressed girder, the expansion due to ASR takes place in other directions, and the orientation of the resulting cracks is determined by the confining stress direction. Thus, it is expected that crack patterns from frost damage are different for specimens tested in the laboratory and in the field, as the small test specimens are unrestrained during frost action, whereas the concrete in field typically experiences some kind of confinement. The difference in crack patterns cannot be interpreted as a difference in mechanism leading to frost damage.

The aim of the present study is to investigate if the confinement during freeze/thaw action influences the developed crack pattern. The study is carried out as an experimental study, where concrete specimens with and without confinement are subject to accelerated freeze/thaw testing in the laboratory.

2. Materials and methods

When choosing a concrete composition for the present study, there were two things to consider. On one hand, the concrete for testing should not be frost resistant; if no damage evolves during the tests, it will not be possible to examine if there is a difference in crack patterns. On the other hand, the concrete should not be too frost susceptible, because if the concrete completely disintegrates during testing, it will not be possible to investigate the crack patterns either.

Air void structure and w/c ratio are two important factors for concrete frost resistance [3]. It was decided to test concrete with w/c ratio 0.45 without air entrainment. A similar mix had been used several times for freeze/thaw testing in our laboratory. Here, the omission of air entrainment resulted in concrete with poor frost resistance, but the concrete was still coherent after 56 freeze/thaw cycles. Moreover, in Denmark, concrete with w/c ratio 0.45 is a realistic concrete for outdoor structures; 0.45 is the maximum w/c ratio for concrete in environmental class A (aggressive environment), which includes combined salt and frost exposure [4].

The mix design is shown in table 1:

Table 1: Mix design for concrete (w/c = 0.45). Aggregates are saturated and surface dry.

Constituent	**Type**	**Density [kg/m³]**	**Mass [kg/m³ concrete]**
Cement	CEM I 52.5 N	3160	475
Water	Tap water	1000	214
Sand	Sea dredged sand (class E)	2640	841
Coarse aggregate, 4-8 mm	Crushed granite (class E)	2710	168
Coarse aggregate, 8-11 mm	Crushed granite (class E)	2720	673

The concrete was mixed in a pan mixer with a batch size of 45 l. The air content in the fresh concrete was 0.7% (measured with a pressure-meter). This corresponded well with the expected natural air content of approximately 1%. Three Ø150 x 300 mm concrete cylinders were cast (labelled I, II, and III). From time of casting to time of testing, the curing conditions followed the curing regime of the reference method in [1].

21 days after casting, 2 cylindrical discs, 50 mm thick, were cut from the middle part of each concrete cylinder. For each disc, a rubber sleeve was glued on the disc perimeter to make it possible to establish a liquid reservoir on the top of the specimen. A rubber sheet was glued to the bottom of the disc. The discs were labelled REF and CLAMP, respectively:

- REF: The specimen was externally unrestrained during freeze/thaw testing, as is the normal test condition. This specimen served as reference of the experiment.
- CLAMP: 2 hose clamps were placed around a concrete disc, each clamp being 25 mm wide. In this way the concrete was subjected to moderate external compression, and concrete expansion became restricted in the radial direction, see figure 1 (left).

Figure 1: Specimen with hose clamps before (left) and after (right) all surfaces except the test surface had been covered with thermal insulation.

The clamps were mounted 28 days after casting, just before the test surfaces were covered with 3 mm de-ionised water. The clamps were tightened by hand with a hex key wrench. The compression enforced by the hose clamps on the concrete specimens was not measured. It was anticipated that the resulting compressive stress in the concrete was small relative to the concrete compressive strength.

31 days after casting, all surfaces except the test surface were covered with thermal insulation, and the de-ionised water was replaced with 3% NaCl solution, before the specimens were placed in a freezing cabinet. The clamps were also covered with insulating material to prevent the metal clamps from forming thermal bridges that would spoil the one-dimensional heat transport through the specimen, see figure 1 (right). In the freezing cabinet, the specimens were exposed to repeated freezing and thawing with temperature cycles complying with [1]. Scaling was collected at intervals as specified in the test standard.

After 33 freeze/thaw cycles, two specimens, one from each of the test series REF and CLAMP, were removed from the freezing cabinet to prepare epoxy impregnated plane sections.

3. Results

Results from the freeze/thaw scaling tests are shown in figure 2.

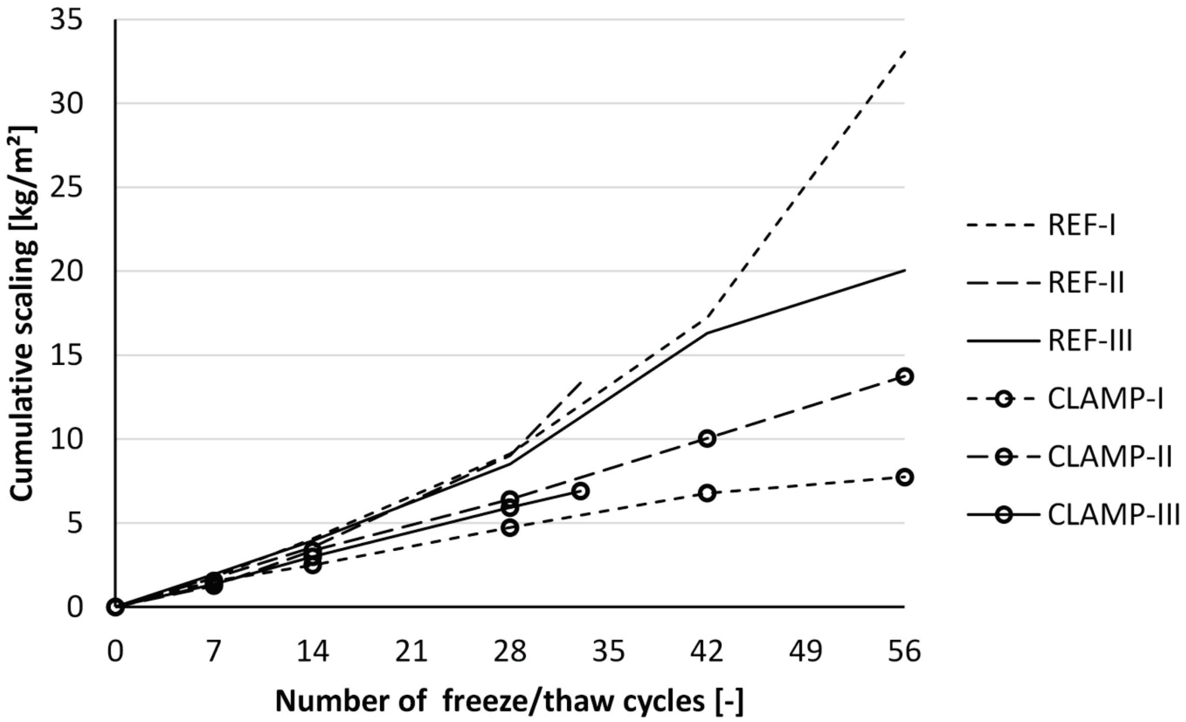

Figure 2: Development in accumulated amount of scaled material. Specimens REF-II and CLAMP-III were removed from the freezing chamber after 33 freeze/thaw cycles.

After 28 cycles, the results become more uncertain. After removal of specimens for epoxy impregnation, the areas of test surface for each series REF and CLAMP no longer fulfil the Danish requirement for minimum test surface for the test (minimum 42,000 mm²). Moreover, problems with leakage were discovered for CLAMP-I (detected when collecting scaling after 28 cycles), and REF-III (detected after 42 cycles). This may explain why the accumulated scaling for CLAMP-I is the lowest of the CLAMP series, and REF III shows the lowest scaling of the REF series; if the concrete surface is not covered with NaCl solution in every freeze/thaw cycle, it reduces the amount of scaling.

Figure 3 shows the epoxy impregnated plane sections for the specimens REF-II and CLAMP-III. The pictures are scaled to the same size. The reason why the height of CLAMP-III is slightly larger than the height of REF-II is because several millimetres of the test surface of REF-II had scaled off.

Figure 3 also shows analyses of crack orientation made with the method described in [5]. REF-II is cracked throughout the specimen, but for CLAMP-III, a large area at the centre of the specimen is uncracked. To make the analyses comparable, they are for both specimens based on the upper 300 pixel rows (approximately 12 mm), corresponding to the cracked area of CLAMP-III beneath the test surface. The orientation 0° / 180° corresponds to cracks parallel to the test surface.

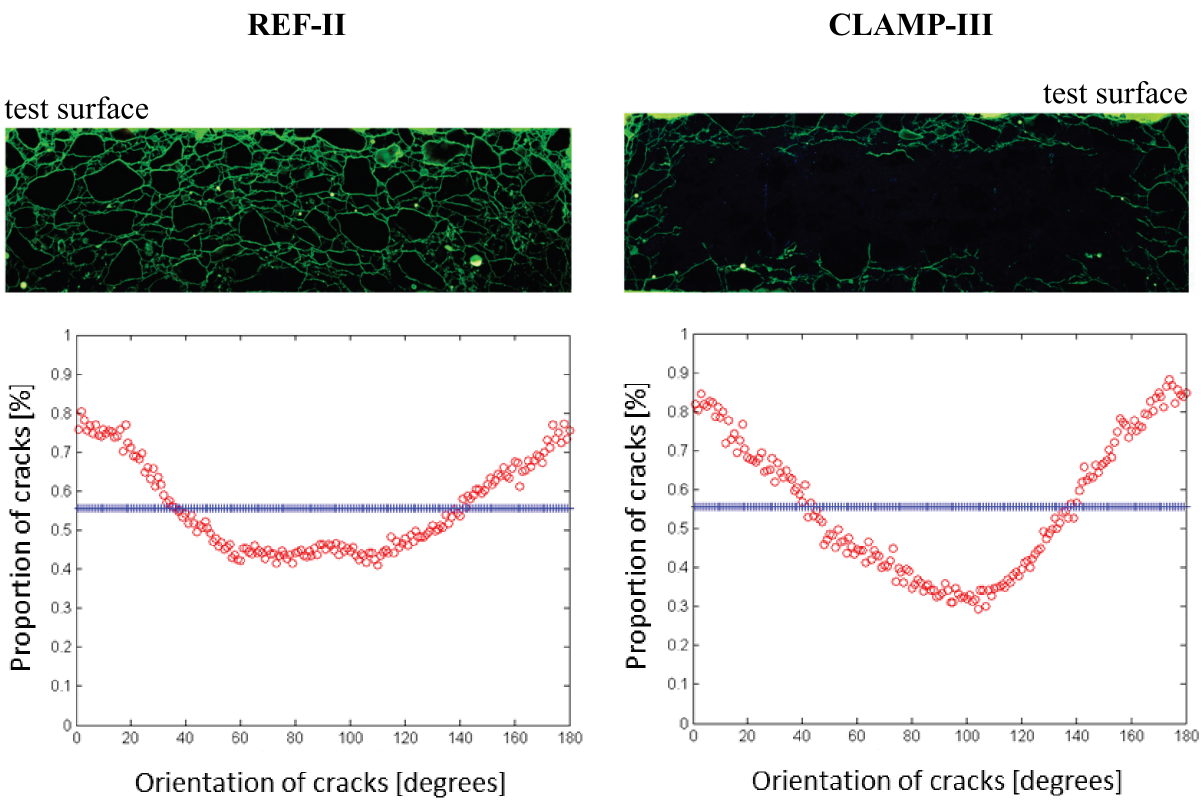

Figure 3: Top: Epoxy impregnated plane sections under UV light (width of each plane section is 150 mm). Bottom: Diagrams showing distribution of crack orientations. Crack orientation 0° / 180° corresponds to cracks parallel to the test surface. Horizontal lines at 1/180 = 0.56% correspond to random crack orientation.

4. Discussion

Though the REF-II specimen had not fallen to pieces during the 33 freeze/thaw cycles, the epoxy impregnated plane section showed that it was completely cracked from top to bottom. Based on a purely visual inspection, the crack orientation was judged to be "random". However, the image analysis (figure 3, left) shows that there tend to be more cracks parallel to the test surface than perpendicular to the surface. Some of the cracks follow the interfacial transition zones of the coarse aggregates, so one possible explanation is that this outcome is due to the casting direction. The coarse aggregate was crushed granite, where some of the particles are flaked; if they systematically take bearing in a certain direction, e.g. when the moulds are vibrated during casting, this may induce a systematic trend in crack orientation. Another possible explanation may be the geometry of the test specimens. The REF specimens are not subject to an outer constraint on specimen movement. But the geometry where the specimen is wider than it is tall may restrict movements more in one direction than in others.

When comparing the observed distribution of crack orientations for REF and CLAMP, there are more surface parallel cracks and less cracks perpendicular to the surface for the CLAMP specimen than for the REF specimen. If even the very moderate confinement that is achieved by the manual tightening of the hose clamps has an effect on the resulting crack orientation, this supports hypothesis B in preference to hypothesis A.

However, the most striking difference between the two specimens is not the difference in crack orientation but the extent of damage. The CLAMP specimen is not as heavily damaged as the REF specimen. The CLAMP specimen is cracked up to 10-15 mm from all free surfaces of the specimen, but further away from the surfaces, no cracks are seen. This is probably related to the availability of free water for ice formation inside the concrete. Cracks perpendicular to the test surface contribute to water transport into the concrete, whereas cracks parallel to the surface do not. Moreover, it may also play a part that for the REF specimen, there are more favourable conditions for widening the cracks during frost action, so they can transport more water, because the movement of the specimen is unrestricted. According to [6], mechanical stress has only a small effect on concrete permeability, as long as the stress level is less than 40% of the concrete strength. At higher stress levels, the mechanical action may lead to cracking, thereby increasing the permeability several orders of magnitude. The crack width also has a pronounced effect.

During the freeze/thaw test, surface scaling was regularly collected, though surface scaling was not the primary focus of the study, as hypotheses A and B do not relate to scaling. The collection of surface scaling was mainly seen as a quality control to identify if one specimen behaved very different from the others e.g. due to casting errors. The results presented in figure 2 show a significant difference in scaling for specimens with and without hose clamps. In the first part of the test period (collection after 7 and 14 freeze/thaw cycles), the amount of scaling of the CLAMP specimens is 20-25% less than the scaling of the REF specimens. It is likely that the confinement imposed by the hose clamps is reduced over time, because the clamps were not tightened during the freeze/thaw test period. If the confinement is relieved over time, the effect of the hose clamps should also level off, but this does not seem to be the case. Actually, the scaling of the REF specimens seems to accelerate, whereas for the CLAMP specimens, the amount of scaling per unit of time is almost constant, and after completion of the 56 freeze/thaw cycles, the cumulated amount of scaling for the CLAMP specimens are less than 50% of the cumulated amount for the REF specimens.

The difference in scaling for specimens with and without hose clamps is surprising, and there is no obvious explanation for it. It may be because surface scaling is not a pure surface phenomenon; the surface scaling may depend on e.g. the general moisture state of the concrete, and it is likely that the REF specimens are more wet than the CLAMP specimens, as outlined above.

If the experiment is repeated in the future, the hose clamps should be tightened with a torque wrench, or other measures should be taken to ensure better control of the stress situation. The stress situation may change during the experiment. If for example the concrete expands due to frost action, the clamping stress will increase, and the use of a torque wrench cannot prevent this. However, using a torque wrench set at a certain torque would ensure a more uniform start situation for all specimens, and the tightness of the clamps can be adjusted during the test period.

It is thought provoking that a small change such as mounting two hose clamps on a test specimen and thereby introducing a modest confinement can change the test result 25% or more. Luckily, it is normally on the safe side to perform freeze/thaw testing on unconfined specimens, as most concrete in real structures is placed under compression, which this study points to will reduce the extent of damage. In recent years, it has become popular to study combinations of load, for example the effect of freezing and thawing on fracture energy [7], shear resistance [8], pre-stress loss [9], and fatigue [10] (and other examples can also be found in [11-13]). The present study urges caution when interpreting and extrapolating these results, especially if the loads are not imposed simultaneously. If the concrete is exposed to freezing and thawing before it is subjected to mechanical load, the result probably differs from what would have been obtained, if freeze/thaw action had taken place at the same time as the mechanical load.

5. Conclusion

In the present study, hose clamps were mounted on 3 of 6 cylindrical specimens prior to a standardised freeze/thaw test. The hose clamps introduced compressive stress in the radial direction (the stress level being small relative to the compressive strength of the concrete) and confined specimen expansion during the test. The results show that confinement can change the outcome of a freeze/thaw test. The outcome is changed as regards extent of internal cracking, crack orientations, and amount of surface scaling.

The results can explain why the crack patterns of concrete specimens tested in the laboratory differ from crack patterns that can be observed in structures in the field made of concrete that is not frost resistant. The difference in crack patterns does not arise from different frost damage mechanisms in the two situations. The difference is probably due to different stress situations, because concrete in a structure is confined during frost action whereas concrete tested in the laboratory is virtually unconfined.

Acknowledgement

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